

# Measurement of $B_c^\pm$ Mass and Lifetime at LHCb

Jibo HE

(on behalf of the LHCb collaboration)

Laboratoire de l'Accélérateur Linéaire, Université Paris-Sud 11, CNRS/IN2P3  
Université Paris-Sud 11, Bâtiment 200, 91898 Orsay cedex, France, Jibo.He@cern.ch

The  $B_c^\pm$  mass and lifetime measurements using the decay  $B_c^\pm \rightarrow J/\psi \pi^\pm$  at the LHCb experiment were studied. About 310 signal events are expected for a data set which corresponds to an integrated luminosity of  $1 \text{ fb}^{-1}$ , with a  $B/S$  ratio equal to 2. Based on these data, the  $B_c^\pm$  mass and lifetime can be measured with expected statistical errors below  $2 \text{ MeV}/c^2$  and  $30 \text{ fs}$ , respectively.

## 1 Introduction

The  $B_c^{+a}$  meson is the ground state of the meson family formed by two different heavy flavor quarks, the anti- $b$  quark and the  $c$  quark. The mass of the  $B_c^+$  meson has been estimated theoretically to be in a range of  $6.2\text{-}6.4 \text{ GeV}/c^2$  [2]. Recently unquenched lattice QCD [3] gave the most accurate prediction of  $M(B_c^+) = 6278(6)(4) \text{ MeV}/c^2$ , where the first error is statistical, and the second is systematic. The  $\bar{b}c$  mesons are open-flavored and the excited states below the  $BD$  threshold can decay only through the electromagnetic or hadronic interactions into the ground state,  $B_c^+$ , which can decay only weakly and has a relatively long lifetime. The estimated  $B_c^+$  lifetime is in a range of  $0.4\text{-}0.8 \text{ ps}$  [2]. At present, the best prediction is given by QCD sum rules [4]:  $\tau(B_c^+) = 0.48 \pm 0.05 \text{ ps}$ . Since the  $\bar{b}c$  mesons carry two different heavy flavor quarks, their production [2] is more difficult than that of the heavy quarkonia. Including the contributions from the excited states, the cross section of the  $B_c^+$  meson at LHC was estimated [5] to be at a level of  $1 \mu\text{b}$ , and is one order higher than that at Tevatron. This means that  $O(10^9)$   $B_c^+$  mesons can be anticipated with  $1 \text{ fb}^{-1}$  of data at LHC, which is sufficient to study the  $\bar{b}c$  meson family systematically.

The  $B_c^+$  meson was observed in the semileptonic decay modes  $B_c^+ \rightarrow J/\psi(\mu^+\mu^-)\ell^+X$  ( $\ell = e, \mu$ ) by CDF [6] at Tevatron. The measured mass and lifetime are consistent with the theoretical predictions. More precise measurements of the  $B_c^+$  mass have been performed recently using the fully reconstructed decay  $B_c^+ \rightarrow J/\psi(\mu^+\mu^-)\pi^+$  by CDF [7] and D0 [8], giving  $M(B_c^+) = 6275.6 \pm 2.9(\text{stat.}) \pm 2.5(\text{syst.}) \text{ MeV}/c^2$  and  $M(B_c^+) = 6300 \pm 14(\text{stat.}) \pm 5(\text{syst.}) \text{ MeV}/c^2$  respectively. The  $B_c^+$  lifetime measurements using the semileptonic decay were also updated with more data, giving  $0.448_{-0.036}^{+0.038}(\text{stat.}) \pm 0.032(\text{sys.}) \text{ ps}$  by D0 [9] and  $0.475_{-0.049}^{+0.053}(\text{stat.}) \pm 0.018(\text{sys.}) \text{ ps}$  by CDF [10].

In this paper, we report our performance study of the  $B_c^+$  mass and lifetime measurements using the exclusive reconstruction of the decay  $B_c^+ \rightarrow J/\psi(\mu^+\mu^-)\pi^+$  at LHCb. The LHCb detector is described elsewhere [11], hereafter is a summary of the LHCb detector performances which are relevant to this study. Based on Monte Carlo studies, the relative momentum resolution  $\delta p/p$  was found to be  $0.35\%\text{-}0.55\%$ , depending on the momentum. The primary vertex can be measured with a precision of about  $10 \mu\text{m}$  in the plane transverse to the beam line, and of about  $60 \mu\text{m}$  in the beam direction. The average resolution of the impact parameter respect to the primary vertex can be parameterized as  $\sigma_{\text{IP}} = [14 + (35/p_T)]$

---

<sup>a</sup>Charge conjugate states are implied throughout this paper, if not specified differently.

$\mu\text{m}$  where  $p_T$  is the transverse momentum respect to the beam direction expressed in  $\text{GeV}/c$ . The muon identification efficiency was measured to be  $\varepsilon(\mu \rightarrow \mu) = 94\%$  with a misidentification probability  $\varepsilon(\pi \rightarrow \mu) = 3\%$ .

## 2 Event selection

The simulation of the  $pp$  collision and the subsequent hadronization were performed with PYTHIA [12].  $B_c^+$  meson was generated with a dedicated  $B_c$  generator, BCVEGPY [13]. The decay of any  $b$  hadron produced was done by EvtGen [14]. The response of the detector was simulated by GEANT4 [15]. In this study, the specific  $b \rightarrow J/\psi(\mu^+\mu^-)X$  (including  $B_d \rightarrow J/\psi X$ ,  $B_s \rightarrow J/\psi X$ ,  $B_u \rightarrow J/\psi X$ ,  $\Lambda_b \rightarrow J/\psi X$ ), the inclusive  $J/\psi(\mu^+\mu^-)$  and inclusive  $b\bar{b}$  MC data samples were simulated for the background study.

The event selection [16] began with selection of good tracks based on the  $\chi^2$  of the track fit, and requiring a  $p_T$  greater than  $0.5 \text{ GeV}/c$ . A pair of two tracks with opposite charges and identified as  $\mu$  were used to reconstruct the  $J/\psi$  meson.  $J/\psi$  candidates were required to have an invariant mass in the range from  $3.04$  to  $3.14 \text{ GeV}/c^2$  and a vertex fit quality of  $\chi^2/\text{ndf} < 9$ . Then a track identified as pion from the rest of the event was combined with the  $J/\psi$  candidate to reconstruct the  $B_c^+$  meson with a vertex fit cut of  $\chi^2/\text{ndf} < 12$ . The impact parameter significance of the reconstructed  $B_c^+$  track with respect to the production vertex must be less than 3. For events with more than one primary vertex, the production vertex is given by the primary vertex to which the  $B_c^+$  candidate has the smallest impact parameter. To suppress combinatorial background further,  $p_T(\mu)$  was required to be greater than  $1.0 \text{ GeV}/c$ ,  $p_T(\pi)$  and  $p_T(B_c^+)$  were required to be greater than  $1.6 \text{ GeV}/c$  and  $5.0 \text{ GeV}/c$  respectively, and the impact parameter significance of the  $\pi$  and  $J/\psi$  mesons were required to be greater than 3.0 and 3.5 respectively.

The total reconstruction efficiency for the signal, including the trigger efficiency, was found to be  $(1.01 \pm 0.02)\%$ . In the  $M(B_c^+) \pm 80 \text{ MeV}/c^2$  (about  $\pm 3\sigma$ ) mass window, which was regarded as the signal region, the background to signal ratio  $B/S$  with 90% confidence level is 1 to 2. The upper limit of  $B/S$  was used in the following study. One can expect about 310 signal events with  $1 \text{ fb}^{-1}$  of data assuming the  $B_c^+$  total production cross section  $\sigma(B_c^+) = 0.4 \text{ } \mu\text{b}$  and  $\text{BR}(B_c^+ \rightarrow J/\psi\pi^+) = 1.3 \times 10^{-3}$ .

## 3 Mass measurement

To improve the  $B_c^+$  mass resolution, the  $J/\psi$  mass constraint vertex fit was used in the mass measurement.  $M(B_c^+) \pm 300 \text{ MeV}/c^2$  mass window was used in the following study. The un-binned maximum likelihood method was implemented to extract the  $B_c^+$  mass. The invariant mass distribution of the signal was modeled by a single Gaussian, that of the background was parameterized as a first order polynomial.

For the fit the signal events were taken from the signal data sample with the full Monte Carlo simulation and the background events were generated by a standalone simulation using the invariant mass distribution obtained from the full Monte Carlo simulation. Both the signal and the background were normalized to  $1 \text{ fb}^{-1}$  of data. The fit gives the  $B_c^+$  mass to be  $M(B_c^+) = 6399.6 \pm 1.7 \text{ (stat.) MeV}/c^2$ , which is in good agreement with the input value of  $6400 \text{ MeV}/c^2$ . The result of the fit is shown in Figure 1.

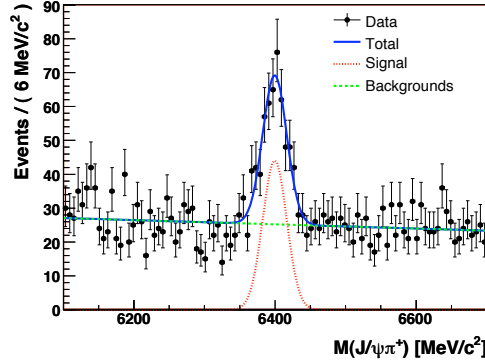


Figure 1: The  $B_c^+$  candidate mass distribution together with the result of the fit described in the text.

#### 4 Lifetime measurement

The  $J/\psi$  mass constraint vertex fit biases the  $B_c^+$  decay vertex position because of the final state radiation in the  $J/\psi$  decay and the energy loss of particles. As a consequence, the  $J/\psi$  mass constraint vertex fit would bias the  $B_c^+$  lifetime and was not used in the lifetime study.

A combined mass-lifetime fit was used to measure the  $B_c^+$  lifetime. The invariant mass distributions for the signal and the background were obtained as in the mass measurement. The proper time ( $t$ ) distribution of the signal was described by an exponential function smeared by resolution and multiplied by an acceptance function  $\varepsilon(t)$  describing the distortion of  $t$  distribution caused by the trigger and offline event selection. The function form was derived from an independent Monte Carlo sample. The  $t$  distribution of the background was parameterized by the "KEYS" (Kernel Estimating Your Shapes) method [17]. The proper time resolution ( $\sigma_t$ ) distributions of the signal and the background were also considered to avoid the potential bias caused by the so called Punzi effects [18]. The fitting framework was tested with a standalone simulation program. The pull of the  $B_c^+$  lifetime was found to follow a Gaussian distribution with  $\mu = 0.004 \pm 0.010$  and  $\sigma = 1.0122 \pm 0.0072$ , which is consistent with the Normal distribution.

As shown in Section 1, the resolution of the impact parameter depends on the transverse momentum. Therefore, the impact parameter significance and the proper time acceptance  $\varepsilon(t)$  depend on the  $p_T(B_c^+)$  distribution. In order to evaluate the systematics introduced by this, a fit to  $B_c^+$ , which was generated with the  $p_T$  distribution predicted for  $B^+$  by PYTHIA, was made using the acceptance function obtained from the  $B_c^+$  data generated by BCVEGPY. Note that the  $p_T(B_c^+)$  spectrum predicted by BCVEGPY is harder than  $p_T(B^+)$  spectrum predicted by PYTHIA. A standalone simulation study shows that in this case the  $B_c^+$  lifetime would be biased by about 0.023 ps.

To reduce the dependence of the lifetime measurement on the  $p_T(B_c^+)$  distribution, the  $p_T(B_c^+)$  was divided into two intervals: 5-12 GeV/c and  $> 12$  GeV/c. The event selection was re-optimized and for the data set with  $p_T(B_c^+) > 12$  GeV/c, the impact parameter significance cuts are changed to  $> 2.0$ ,  $> 2.5$  and  $< 4.0$  for pions,  $J/\psi$  and  $B_c^+$  respectively. The event selection results of the two  $p_T$  intervals are summarized in Table 1. The combined

$p_T$ intervals of $B_c^+$	5-12 GeV/ $c$	$\geq 12$ GeV/ $c$
Total efficiency $\varepsilon_{\text{tot}}$ (including trigger)	$(0.34 \pm 0.01) \%$	$(0.86 \pm 0.02) \%$
Signal yield ( $1 \text{ fb}^{-1}$ @ 14 TeV)	100	260
$B/S$ @ 90% CL	3 to 6	0.6 to 1.2

Table 1: Summary of the event selection results in the two  $p_T(B_c^+)$  intervals. The total efficiency  $\varepsilon_{\text{tot}}$  in the two  $p_T$  intervals are both defined with respect to the total number of the events in the full  $p_T$  range.

mass-lifetime fit applied simultaneously for the two  $p_T(B_c^+)$  intervals reduces the bias in the lifetime measurement to about 0.004 ps.

The fit to the  $1 \text{ fb}^{-1}$  of data gives  $B_c^+$  lifetime to be  $\tau(B_c^+) = 0.438 \pm 0.027$  (stat.) ps, which is in good agreement with the input value of 0.46 ps. The results of the fit in the two  $p_T(B_c^+)$  intervals are shown in Figure 2.

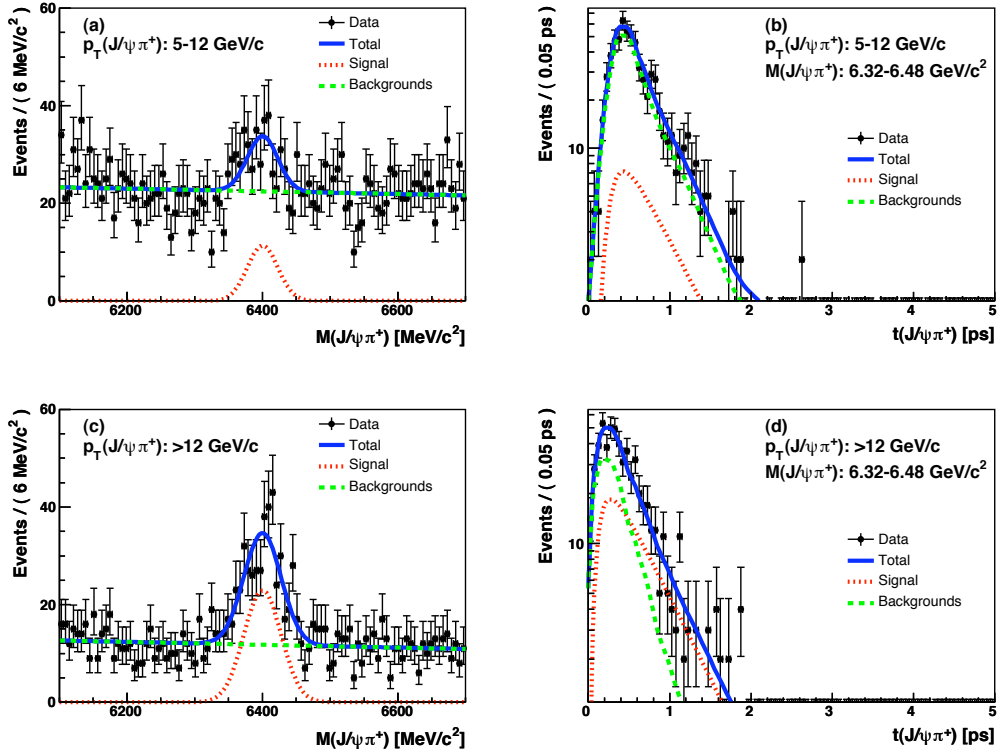


Figure 2: The results of the fit in the two  $p_T(B_c^+)$  intervals. The left column shows the invariant mass distributions, the right column shows the proper time distributions in the signal region.

## 5 Summary

In summary, the event selection of the decay  $B_c^+ \rightarrow J/\psi(\mu^+\mu^-)\pi^+$  at LHCb was studied, about 310 signal events are expected from  $1 \text{ fb}^{-1}$  of data, with a  $B/S$  of 2. Based on the selected data sample, the  $B_c^+$  mass can be measured with an expected statistical error to be below  $2 \text{ MeV}/c^2$ . For the  $B_c^+$  lifetime measurement, to reduce a potential bias caused by the limited knowledge of the  $p_T(B_c^+)$  distribution, the data sample was divided into two  $p_T(B_c^+)$  intervals. The combined mass-lifetime fit performed in these two  $p_T$  intervals simultaneously gives a statistical uncertainty of the  $B_c^+$  lifetime to be below 30 fs.

## References

- [1] Slides:  
<http://indico.cern.ch/contributionDisplay.py?contribId=195&sessionId=5&confId=53294>.
- [2] N. Brambilla et al. Heavy quarkonium physics. arXiv: hep-ph/0412158.
- [3] Ting-Wai Chiu and Tung-Han Hsieh.  $B_s$  and  $B_c$  mesons in lattice QCD with exact chiral symmetry. *PoS, LAT2006*:180, 2007.
- [4] V. V. Kiselev, A. E. Kovalsky, and A. K. Likhoded.  $B_c$  decays and lifetime in QCD sum rules. *Nucl. Phys.*, B585:353–382, 2000.
- [5] Chao-Hsi Chang and Xing-Gang Wu. Uncertainties in estimating hadronic production of the meson  $B_c$  and comparisons between TEVATRON and LHC. *Eur. Phys. J.*, C38:267–276, 2004.
- [6] F. Abe et al. Observation of the  $B_c$  meson in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8 \text{ TeV}$ . *Phys. Rev. Lett.*, 81:2432–2437, 1998.
- [7] T. Aaltonen et al. Observation of the Decay  $B_c^\pm \rightarrow J/\psi\pi^\pm$  and Measurement of the  $B_c^\pm$  Mass. *Phys. Rev. Lett.*, 100:182002, 2008.
- [8] V. M. Abazov et al. Observation of the  $B_c$  Meson in the Exclusive Decay  $B_c \rightarrow J/\psi\pi$ . *Phys. Rev. Lett.*, 101:012001, 2008.
- [9] V. M. Abazov et al. Measurement of the lifetime of the  $B_c^\pm$  meson in the semileptonic decay channel. *Phys. Rev. Lett.*, 102:092001, 2009.
- [10] Measurement of the  $B_c$  Lifetime in  $B_c \rightarrow J/\psi + l + X$  Decays. CDF-note-9294.
- [11] A. Augusto Alves et al. The LHCb Detector at the LHC. *JINST*, 3:S08005, 2008.
- [12] Torbjorn Sjostrand, Leif Lonnblad, Stephen Mrenna, and Peter Skands. Pythia 6.3 physics and manual. 2003.
- [13] Chao-Hsi Chang, Jian-Xiong Wang, and Xing-Gang Wu. An upgraded version of the generator BCVEGPY2.0 for hadronic production of  $B_c$  meson and its excited states. *Comput. Phys. Commun.*, 175:624–627, 2006.
- [14] D. J. Lange. The EvtGen particle decay simulation package. *Nucl. Instrum. Meth.*, A462:152–155, 2001.
- [15] S. Agostinelli et al. GEANT4: A simulation toolkit. *Nucl. Instrum. Meth.*, A506:250–303, 2003.
- [16] Y. Gao, J. He, and Z. Yang. Event selection of  $B_c^\pm \rightarrow J/\psi(\mu^+\mu^-)\pi^\pm$  and estimate of the event yield. CERN-LHCB-2008-059.
- [17] Kyle S. Cranmer. Kernel estimation in high-energy physics. *Comput. Phys. Commun.*, 136:198–207, 2001.
- [18] Giovanni Punzi. Comments on likelihood fits with variable resolution. arXiv: physics/0401045.